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AN ANALYSIS OF EM RAILGUN
CROSS SECTION DESIGNS

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Introduction

Electromagnetic (EM) railguns are of interest to the military due to their ability to achieve muzzle velocities much greater than conventional propellant guns. High velocities are important because they increase the projectile's kinetic energy and are significantly greater than what is currently possible with conventional powder guns. Not only is lethality increased by a higher velocity, but range is increased as well. Also, the lack of propellant in EM guns allows for more stowed rounds and decreases the chances of sympathetic detonation. Should EM guns reach the battlefield, they will increase the effectiveness of the warfighter and reduce the logistic burden on the military as a whole.

The goal of the program in when this research was performed was to build a working full size cantilevered railgun using low risk state of the art technology. While other organizations worked on the power supply and other aspects of the railgun, Benét's goal was to develop ways to build a cantilevered railgun that can contain the rails to as low a rail expansion as necessary for proper operation while also keeping the weight of the tube as low as possible.

In order for a railgun to function properly, the distance between the rails needs to stay nearly constant throughout the length of the shot. The same magnetic force that propels the projectile out the barrel works to pull the rails apart. If they get pulled too far apart, the armature may lose contact with the rails and cause significant problems. Benét's job was to help mitigate this by building a railgun with a stiff cross section that holds the rails together while keeping the overall weight of the system low. To achieve a stiff cross section, Benét incorporated a preload into the wrap of the design. The preload was incorporated to counteract the electromagnetic forces and keep the rails from expanding beyond acceptable limits, and testing and simulations verify that having a preload in the design performs much better than the same design without preload. This was proven through the use of experiments and finite element analysis (FEA) on several designs, but most notably on an adaptation of the XM1 design from a previous Army EM gun program. This paper will discuss the studies and tests performed on the modified XM1 design, as well as give an overview of other designs and analysis methods.

Contents

Design

For the first attempt at building a suitable EM railgun tube, Benét chose to follow the footsteps of others who have put a lot of work into researching the physics of EM guns. The design used was based on the work of IAP Research, Inc. from Dayton, OH and their XM1 design. IAP has been in the EM gun community for many years and has studied various cross sectional designs for the tube. The XM1 design was a culmination of IAP's studies of what materials and configurations worked well electrically, magnetically, structurally, and gave a good bore life. Because the XM1 design was sufficient to handle these issues, Benét decided to use it as the basis for their design and modified it to make it simpler to build and easier to develop a preload in the composite wrap. The "Modified XM1" design consisted of the same five main parts as the original XM1 design: two rails and two insulators contained by a composite wrap. The rails were to be made of either copper or aluminum, the insulators were to initially be made of G-10, and the wrap was to be a carbon fiber/epoxy composite. The cross sectional drawing of this design is shown in Figure 1, with the rails outlined in red, the insulators outlined in green, and the wrap outlined in blue.
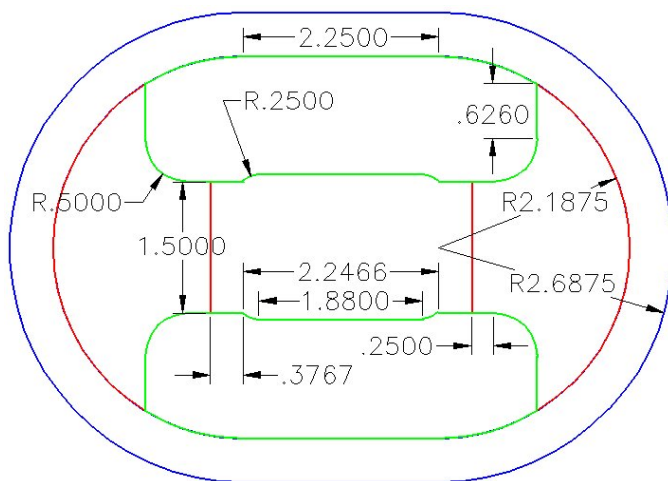
The most important component of this design is the pre-stressed carbon fiber wrap. This preload is what makes this cross section a stiff design and is the most unique aspect of it. Composite wrapped and pre-stressed tubes are not new technologies in themselves, but until recently there has not been a viable technique for wrapping tubes in tension. Because wrapping in tension seemed to be the easiest and most effective way to get the desired results, Benét sought out a method to do this and contacted Automated Dynamics in Schenectady, NY for help. Automated Dynamics developed a winder/tape placement machine with the ability to wrap tubes with a significant amount of tension. The machine applies 250 lbs of tension to a thermoplastic prepreg tape as the tube is wrapped and cures the tape in place using hot nitrogen gas to provide the necessary heat. Because of this cure-in-place technology, the tube does not have to be cured in an autoclave afterwards. The fact that the resin in the prepreg is a thermoplastic rather than a thermoset is what allows the wrapping in tension to work properly.

Figure 1. Drawing of the Modified XM1 Design (dimensions are in inches)

The prepreg tape that Benét used was an IM7 carbon fiber wrap with PEEK resin, which was ½" wide and 0.008" thick. The hoop layers were laid on the tube in tension and cured on the fly such that the winding tension was locked into place. The axial fibers were laid on the tube without tension, one layer for every two hoop layers. Theoretically, this could create a pre-stress of 41.667 ksi based on Equation 1.

$$prestress = \frac{T}{w \cdot t} \cdot \frac{\#\,of\,hoop\,layers}{total\,\#\,of\,layers} = \frac{250\,lbs}{0.5''\cdot 0.008''} \cdot \frac{2}{3} = 41.667\,ksi \qquad (1)$$

The concept behind this design is that the electromagnetic force works against the preload in the wrap as it tries to separate the rails. The preload works with the stiffness of the wrap and gives the gun additional resistance to the repulsive force. Without the preload, the gun would have only the stiffness of the wrap to keep the rails from separating, and it would not perform as well. It is important to note that because of the high pre-stress in this design, the insulators are put into a high state of compression and need to have the thickness and the strength to avoid buckling during wrapping.

Testing

In order to understand this design more and to determine whether or not the preload works with real parts, several stub tubes of this design were made, one of which is shown in Figure 2. In this stub tube, the rails were made from a basic off-the-shelf anode copper and the insulators were made from standard off-the-shelf G-10 fiberglass blocks. The wrap was an IM7 carbon fiber in a PEEK resin. A second stub tube was made with aluminum rails to provide a higher yield strength in the rails.

A 1" thick section was cut from the stub tube with copper rails and pulled apart in a tensile testing machine. Two steel pins contacted the rails and simulated the electromagnetic rail pressure, and a steel clevis on each side connected the pins to the machine and transferred the load to the tube cross section. A knife edge was bonded to the clevis to measure rail expansion since there was no room in the setup to measure it directly. Photographs of this setup are shown in Figure 3.

Figure 2. Photograph of Modified XM1 Stub Tube

The 1" section of the railgun was pulled to just above 30 ksi rail pressure, at which the section of tube could not hold anymore load. It turns out that the rail was too soft to handle these loads because of the type of copper used. This copper was chosen because the time to acquire it was negligible. Unfortunately, it had a yield strength of only about 30 ksi. Therefore, when the rail pressure reached 30 ksi, it was guaranteed to yield. It actually yielded near a 20 ksi rail pressure because of the stress being concentrated around the bends in the rails. Because of this fact, all of the data after about 21 ksi is not very useful.

Benét then tested a 1" section of the stub tube with aluminum rails in order to learn what would happen at higher rail pressures. The test was taken up to 34 ksi rail pressure and the aluminum did not yield like the copper had.

An important part of building the stub tube was to determine how much preload was actually in the tube. The theoretical prediction was 41.667 ksi based on the tension in the carbon fiber tape during winding. A software package, Wind 5.0, jointly developed by the University of Delaware and the Army Research Laboratories for round composite wrapped tubes predicted similar preloads in round tubes of similar size with the same materials. Before the test was performed, the close down of the rails predicted a similar preload. And finally, when the test was finished, the wrap was cut and it separated a certain distance because of the internal loading. Based on that distance, the preload was verified to be about 40 ksi.

Modeling

Several FEA models were created using Abaqus in order to study the preload and other design changes further without having to build each design change. The models were set up with 2D plane strain elements to simulate conditions in a full length railgun, and all of the contact surfaces were frictionless. It is important to note that only elastic properties were used for the materials, so the FEA data does not reflect any yielding of the copper. The purpose of these FEA runs was first to compare the data to experimental data to verify the validity of the FEA data, and then to compare the elastic differences between the no preload and 40 ksi preload cases.

An initial comparison of the data with copper rails showed 40% more expansion in the real part than in the FEA. The reason for this difference was the location of the clip gauge and the elasticity of the setup. After running a 3D model of the setup to account for
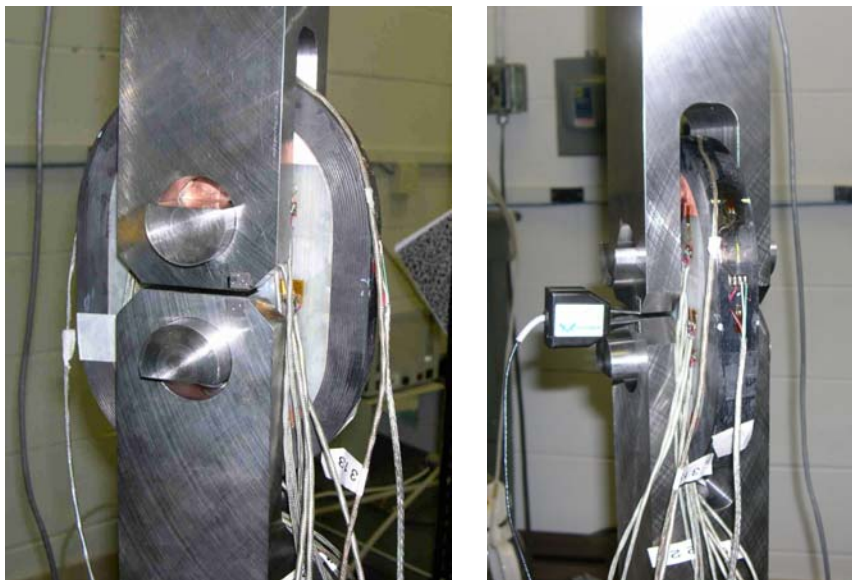

Figure 3. Setup for Tensile Test – Front View and Side View Showing Clip Gauge

its elasticity, the adjusted experimental data matched the FEA data quite well. A comparison plot is shown in Figure 4.

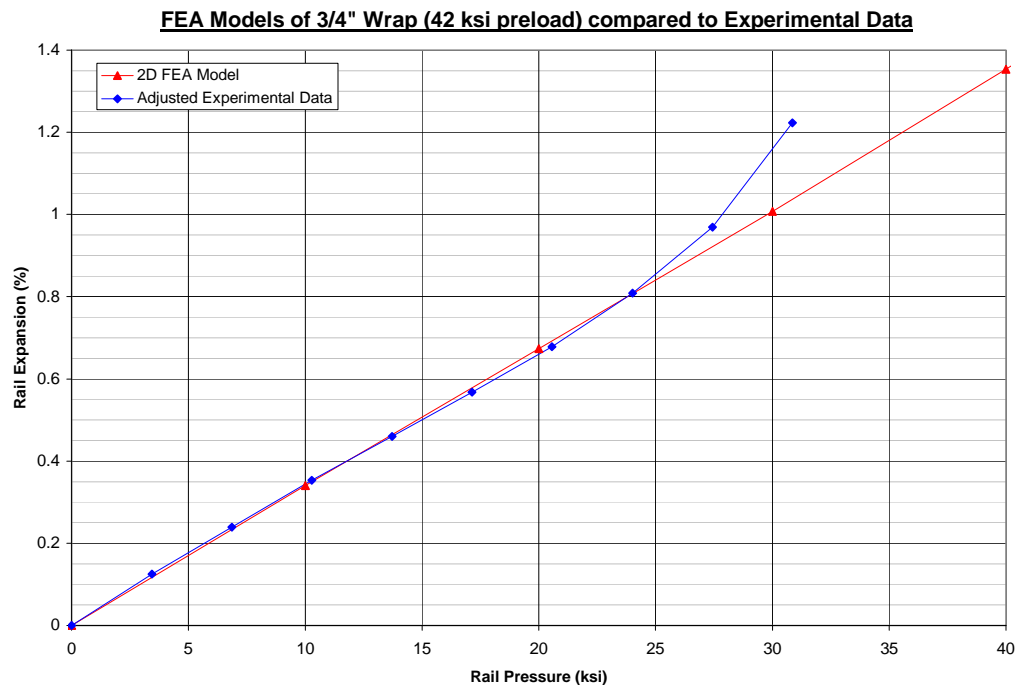**FEA Models of 3/4" Wrap (42 ksi preload) compared to Experimental Data**

Figure 4. Comparison of FEA and adjusted experimental data (Cu rails)

The FEA model matches the experiment almost perfectly in the elastic region of the test, but since it does not incorporate yield data, fails after that point. This is important to understand because rail pressures during firing might reach 35 ksi, and therefore a rail material with a much higher yield strength must be used. Although this design consideration was not important at this phase of testing, it will be very important to account for in the future.

The test with the 1" cross section with aluminum rails did not match up as closely. Figure 5 shows the adjusted experimental data along with the FEA data for the test.

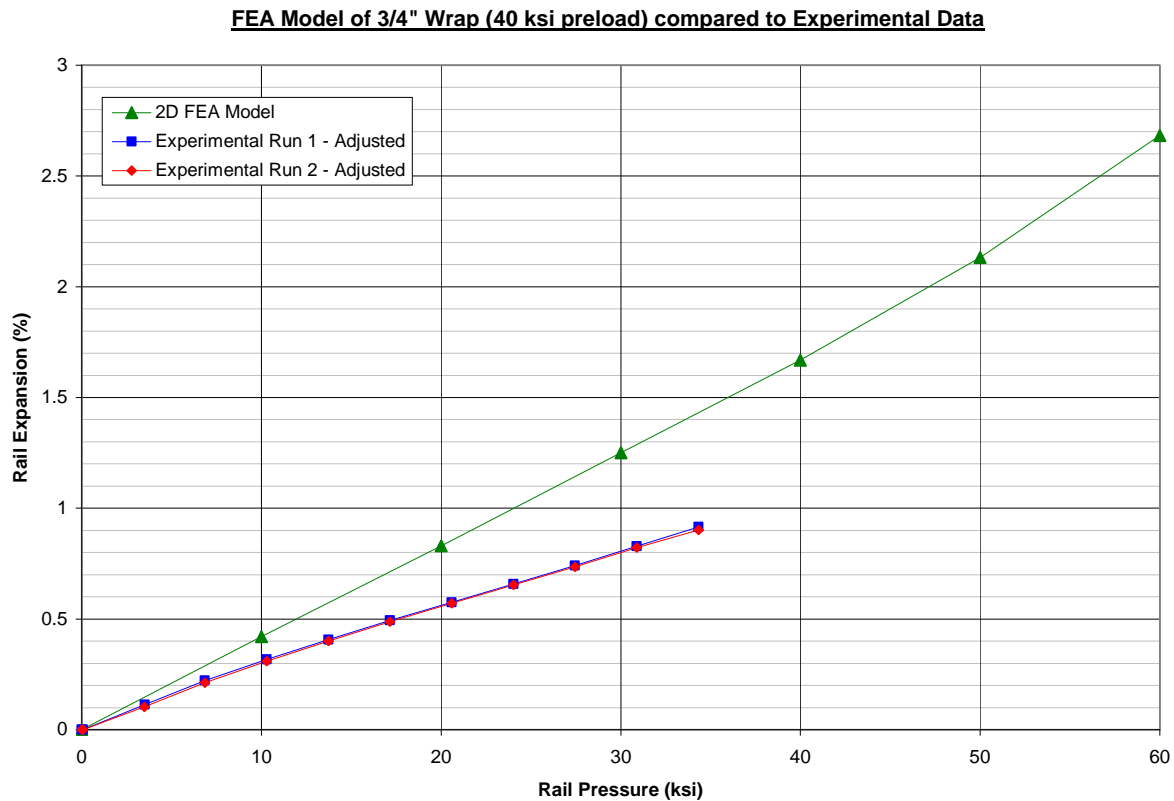**FEA Model of 3/4" Wrap (40 ksi preload) compared to Experimental Data**

Figure 5. Comparison of FEA and adjusted experimental data (Al rails)

There are several things that need to be pointed out about this comparison. First, the experimental data was repeatable as shown by the two tests giving extremely close data. Second, the FEA data shows more rail expansion with aluminum than it did with copper, which should have happened due to the lower modulus of aluminum. Theoretically, the copper piece should have been stiffer than the aluminum piece like the FEA data showed, but the experiment showed otherwise. Despite this difference between theoretical data and experimental data, it is important to note that the FEA models are for the most part accurate and can be used to test basic changes for the Modified XM1 design. It should not be used to acquire final data for any design, but should be used as a tool to compare designs and figure out what effects different changes on the design will have.

Several FEA models were run to demonstrate that the preload is beneficial in keeping rail deflection down. The results of the FEA models with copper rails and a ½" wrap are shown in Figure 6, and the results with copper rails and a ¾" wrap are shown in Figure 7.
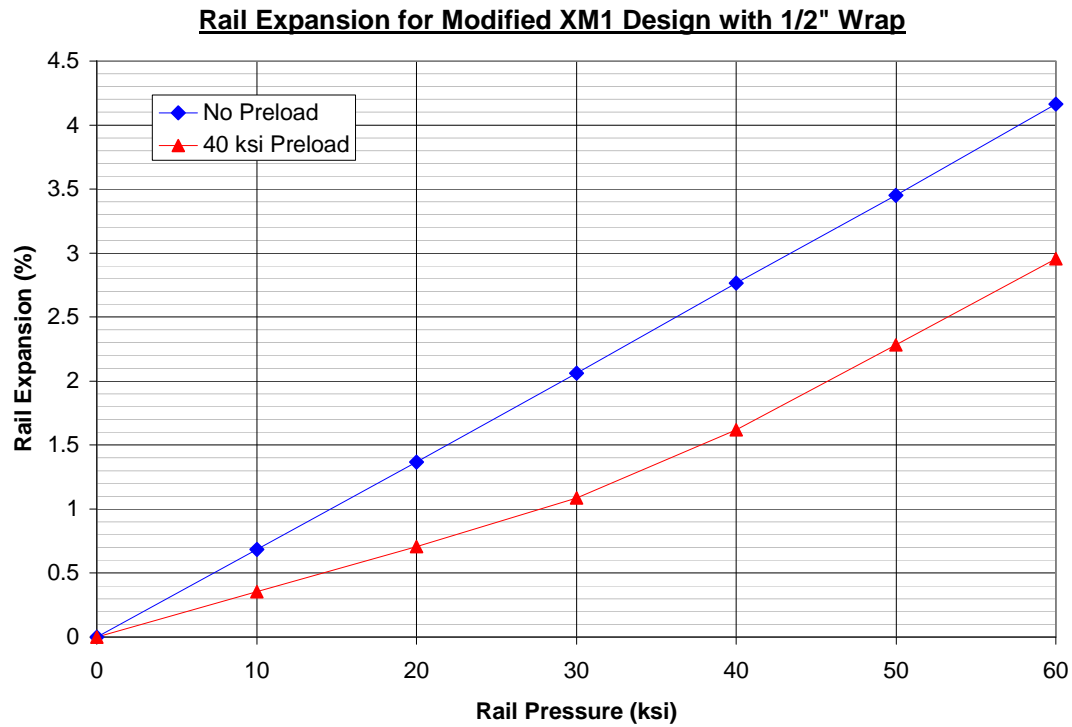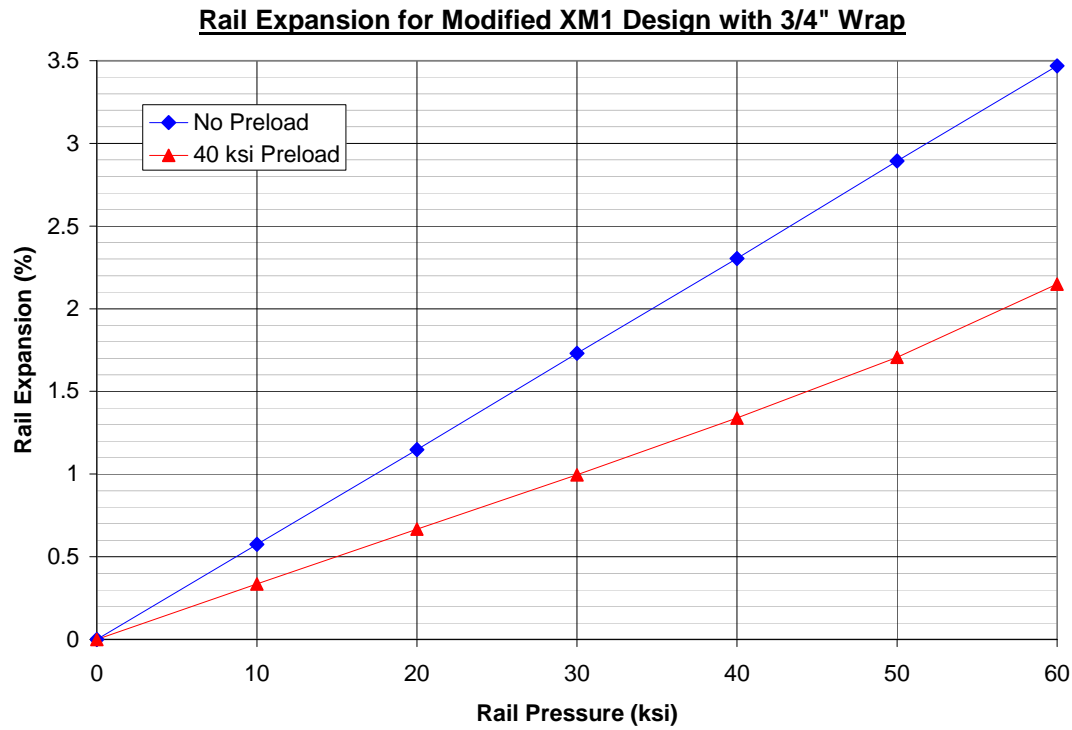
Figure 6. Rail Expansion with ½" Wrap

Figure 7. Rail Expansion with ¾" Wrap

Based on these results, having a 40 ksi preload lowers the rail expansion at 30 ksi rail pressure by 47% for the ½" wrap and 42% for the ¾" wrap. Therefore, the preload will significantly improve the performance of the gun. The decrease in rail expansion will allow the armature to stay in closer contact with the rails. In this design and in other rounded EM gun designs, a preload is desired and will increase the structural integrity of the gun, improve its performance, and lengthen its service life.

Materials

Up to this point, Benét had been using materials that were either on hand or were easy to acquire. The IM7/PEEK used in the wrap is a fairly standard thermoplastic carbon fiber. The G-10 used in the insulator has been used in many laboratory EM guns and is relatively inexpensive and readily available. The anode copper used was off the shelf, and the aluminum was also inexpensive and easy to acquire. For the final design, different materials would need to be studied in order to choose the combination of materials that would produce the best results and survive while doing so.

For the rail, the basic choices were copper and aluminum. The rail material needed to have high strength to avoid yielding during firing and preloading, needed to be a good conductor, and if possible, be light. Anode copper was not strong enough, and aluminum does not have the electrical properties that copper has. Therefore, it was decided that a chromium copper alloy would be used to take advantage of the electrical properties of copper while having a high strength material. The lightness of aluminum was not enough to justify its use.

For the wrap, the higher the modulus of the materials, the lower the rail expansion would be. There was a carbon fiber with twice the modulus of IM7, Dialead K63712, manufactured by Mitsubishi Chemical. But, the main problem with this fiber was that it was unproven and lacked applicable test data. For both of the materials, the design used two hoop fibers for every axial fiber. This could easily be changed in the future.

For the insulator, G-10 was not a viable candidate at all. It is too soft and weak for this application. In order to find a replacement, the previous DOD EM railgun programs were studied and Nextel 610 ceramic fibers were shown to be a good option. They were heavy, but would provide the stiffness and strength needed in the railgun while providing the necessary electrical insulation. Their final design included a 2D fiber lay-up, with two plies in the rail to rail direction for every one ply in the axial direction. The properties used in these models were the properties found by the previous EM gun program.

To determine the extent of the improvements if Dialead K63712 and Nextel 610 fibers were used, several FEA models were run and compared with the original FEA model with IM7 and G-10. The first model had IM7 fibers for the wrap and Nextel 610 fibers for the insulator. The next model had Dialead K63712 as the wrap and Nextel 610 as the insulator. The results are shown below in Figure 8.

Rail Expansion of Modified XM1 Design
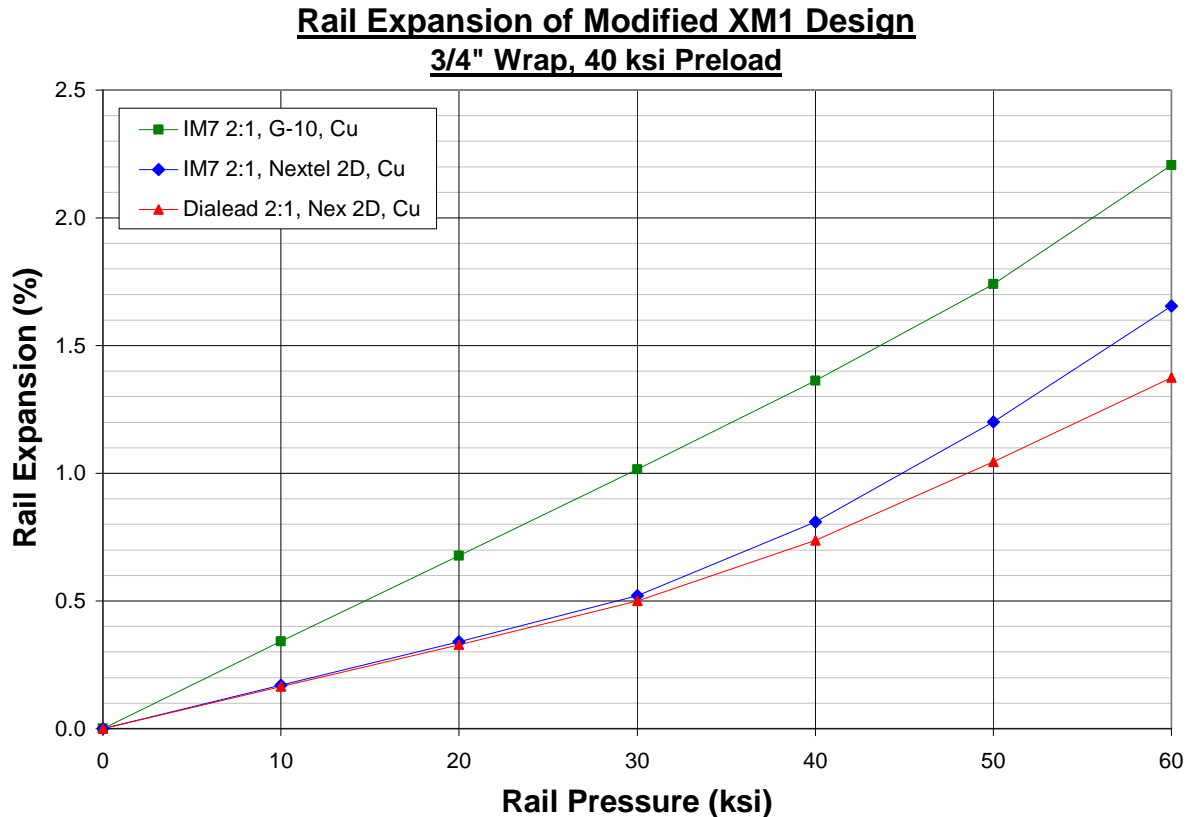### 3/4" Wrap, 40 ksi Preload

Figure 8. Results of changing the materials of the wrap and insulator

The green series in the plot shows the original model with IM7 and G-10. Changing the insulator to Nextel 610 cuts the rail expansion in half. That is a definite improvement over the previous material. Using the Dialead K63712 instead of the IM7 with the Nextel 610 insulator does not provide a great increase in performance. The increase would only be seen well after the operating pressure of the railgun. Therefore, it was decided to move forward with an IM7 wrap, a Nextel 610 insulator, and chromium copper rails.

Modified XM1 Conclusion

Through the use of these experimental studies and the FEA work, it was determined that wrapping an XM1-like design is a viable option for the EM railgun launcher. The results clearly show that wrapping the design in tension increases the ability of the design to minimize rail deflection to a suitable level. Also, the comparison between the experiment and FEA verifies that FEA may be used to study 2D cross sections of the EM railgun launcher in future design iterations with a reasonable certainty of accuracy.

Design Descriptions

Despite the fact that the Modified XM1 design is a good design and should work well for an EM railgun cross section, it was decided other cross section designs should be studied and new ones should be designed in order to gain more of an understanding of the issues involved with the design of a railgun and possibly come up with a better alternative. One reason an alternative might be needed in the future is because of the limitations of the 1.5" by 3" bore size of the XM1 design. This bore size works well for kinetic energy (KE) rounds, but cannot fire high energy (HE) rounds, which have a larger diameter than KE rounds. Therefore, if HE rounds are ever going to be fired from a railgun, a cross section with a wider bore will be necessary. These concepts have been referred to as scalloped designs because many times there is a round scallop cut out of the insulator to allow the larger HE round to go through. The problem with scalloping designs is that the preload loses its effect when material is removed from the insulator. Less material cannot hold as much pressure and therefore the gun cannot perform as well under preload or under loading. Therefore, the desired solution was a cross section that would allow HE rounds to be fired and still be stiff enough to function properly without gaining too much extra weight. Some of the designs on the next few pages are attempts to make a stiff scalloped design and others are different options for a normal bore sized railgun.

It is important to point out a few items about the designs and plots on the next few pages. Each design has a picture and a plot showing its rail expansion under loading. First, yield properties for the materials were not taken into consideration yet. Second, FEA models were run using two basic combinations of materials: soft and stiff. Soft materials include IM7 for the wrap, G-10 for the insulator, and copper for the rails. Stiff materials include Dialead K63712 for the wrap, Nextel 610 for the insulator, and copper for the rails. Aluminum is used for the rail materials in some of the models, and is noted in the plot legends where used. Third, there were two different methods for achieving the prestress in the models. One is the CTE method, which means that a negative coefficient of thermal expansion was chosen based on an artificial one degree temperature increase in the part to cause the wrap to shrink around the core materials and develop the prescribed preload. The *Pre-tension section method applied a load to a section of the wrap to get the proper preload. These methods each have their advantages and disadvantages, but they will not be discussed here. The important thing is that they give the same results, as is shown in Figure 12.
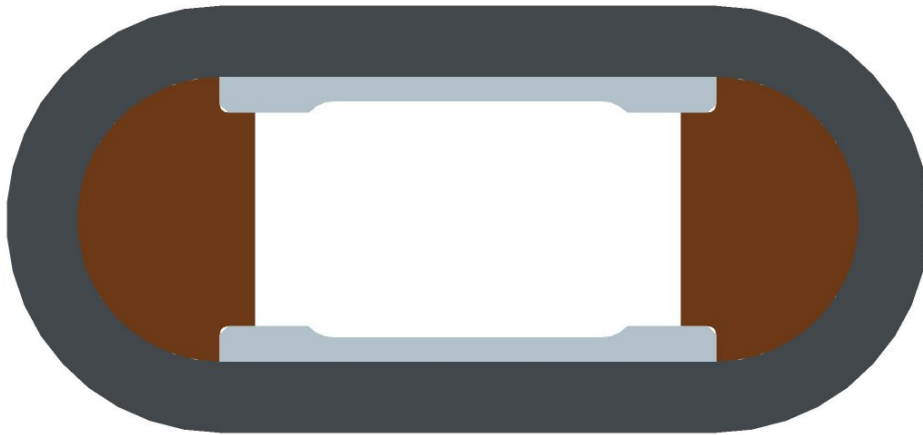
Flat Design

Figure 9. Flat Design

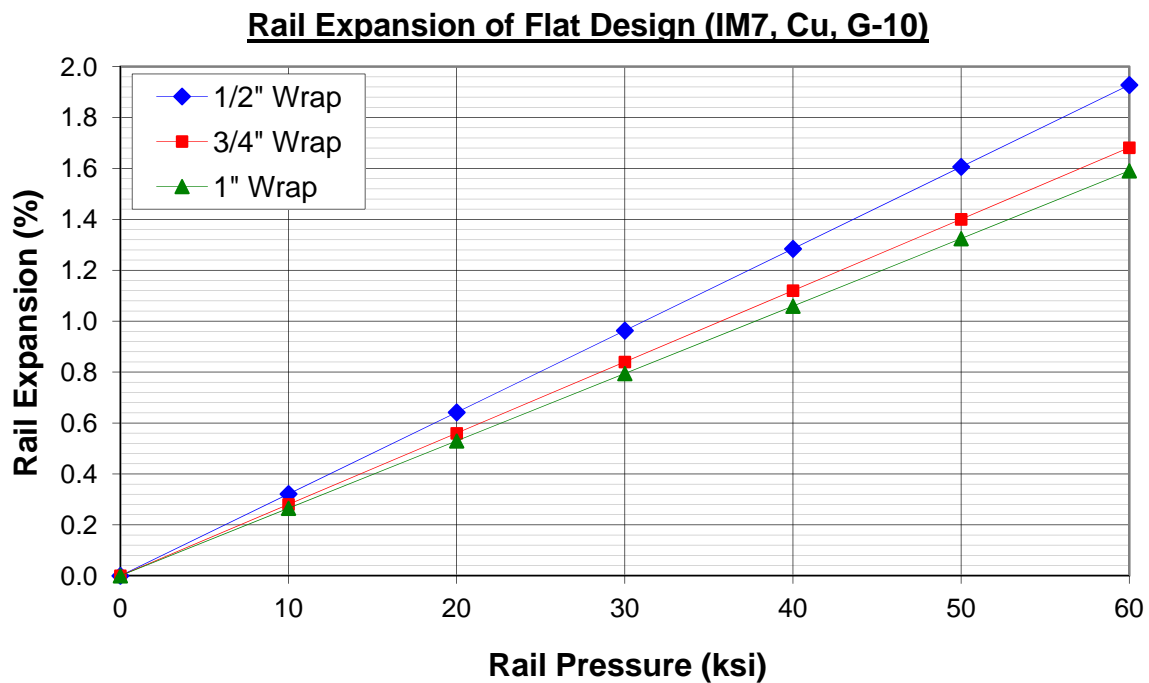**Rail Expansion of Flat Design (IM7, Cu, G-10)**

Figure 10. Flat Design Rail Expansion

The flat design is based on the fact that loading in a railgun is basically only in one direction. Therefore, the resistance to that loading should be in line with the direction of the loading and as close to where it is applied as possible. This minimizes the effects of bending. In this design, the sides of the wrap are very close to the bore, achieving this condition and making a very stiff cross section. It needs no preload to have a high stiffness. The problem with this design is that it cannot resist loading in other directions very well. Plasma pressure would be very difficult for this design to handle should it be present.
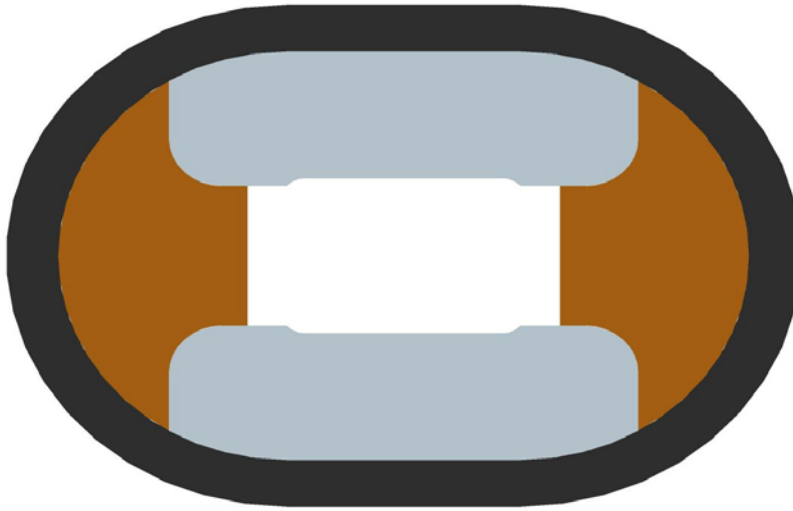
Modified XM1 Design

Figure 11. Modified XM1 Design

Rail Expansion of Modified XM1 Design
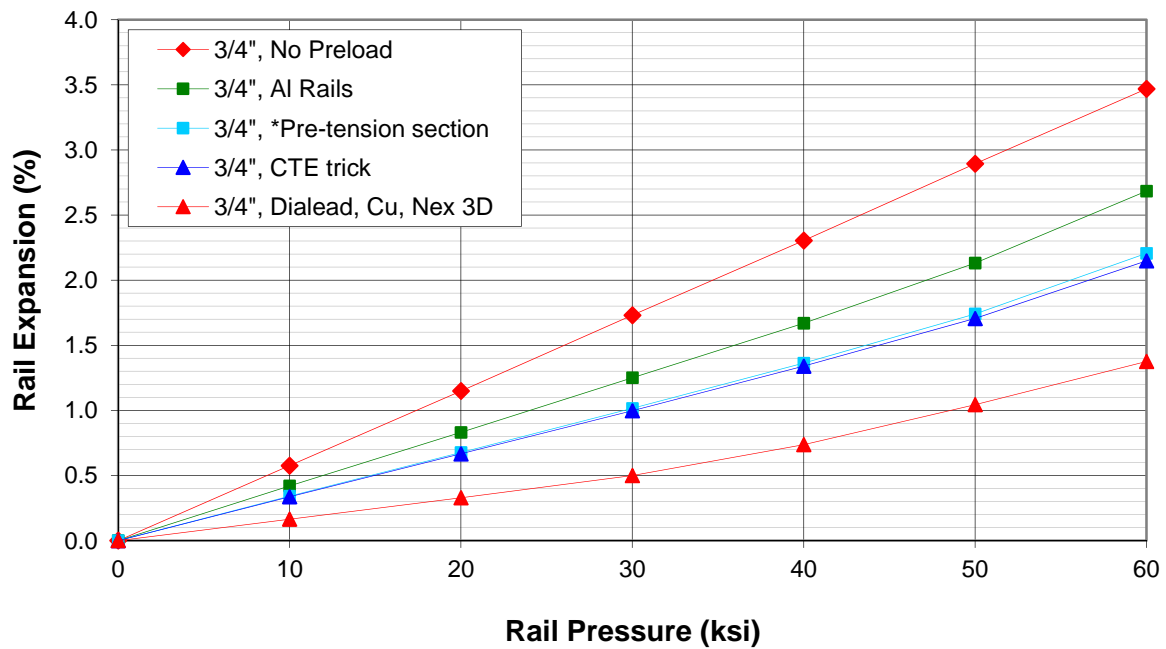#### (IM7, G-10, Cu, and 40 ksi preload except where noted)

Figure 12. Modified XM1 Rail Expansion

The modified XM1 design is an adaptation of the XM1 design developed by IAP Research, Inc. With significant preload and stiff materials, this design can be quite stiff, although not as stiff as the flat design and also heavier.
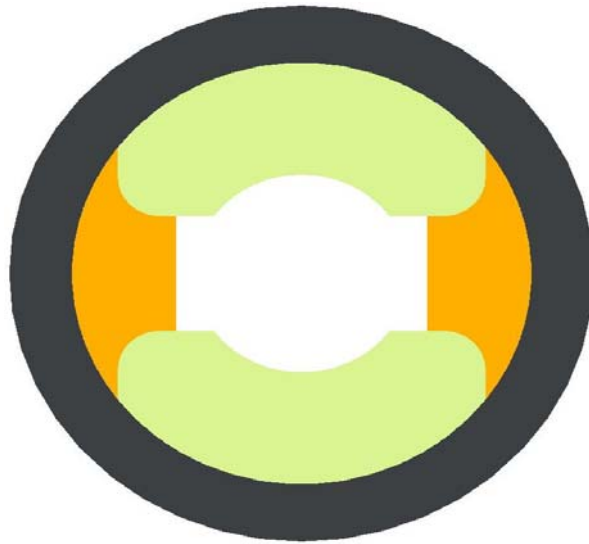
11

Scalloped Round Design

Figure 13. Scalloped Round Design

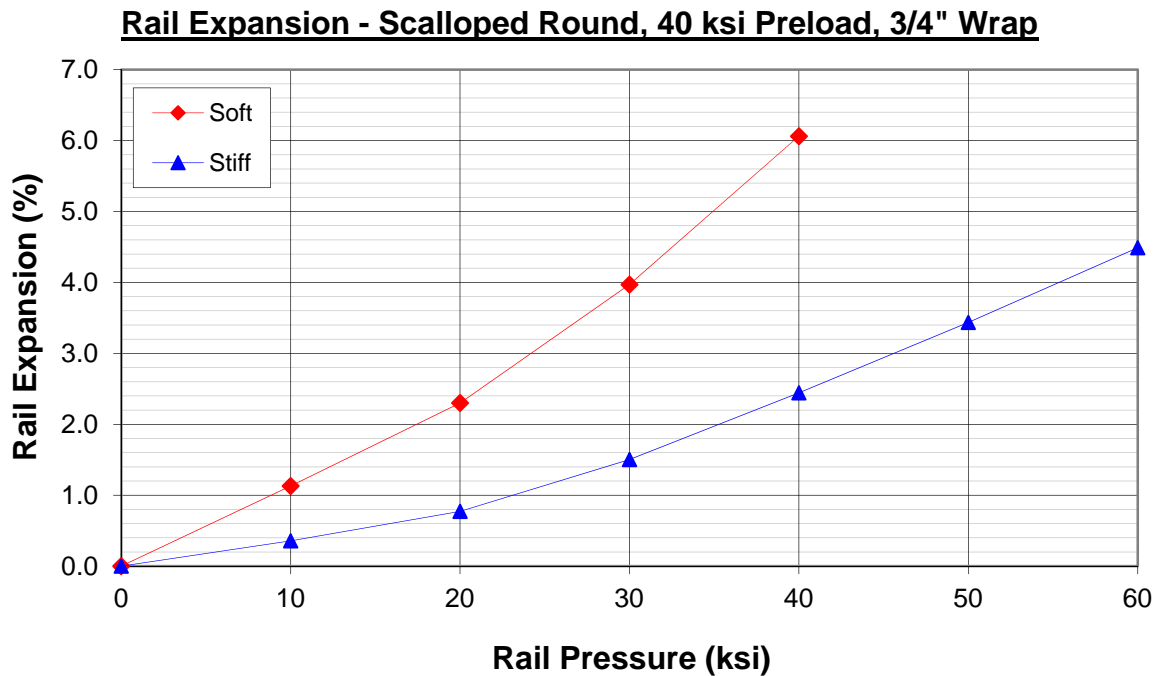**Rail Expansion - Scalloped Round, 40 ksi Preload, 3/4" Wrap**

Figure 14. Scalloped Round Design Rail Expansion

The scalloped round design is an adaptation of the modified XM1 design whose purpose is to incorporate HE rounds through its scalloped bore and make the winding in tension process much easier to achieve. The problem is that the round shape of the gun causes it to lose stiffness with a railgun loading pattern. Round structures tend to oval with very low loads in these conditions.
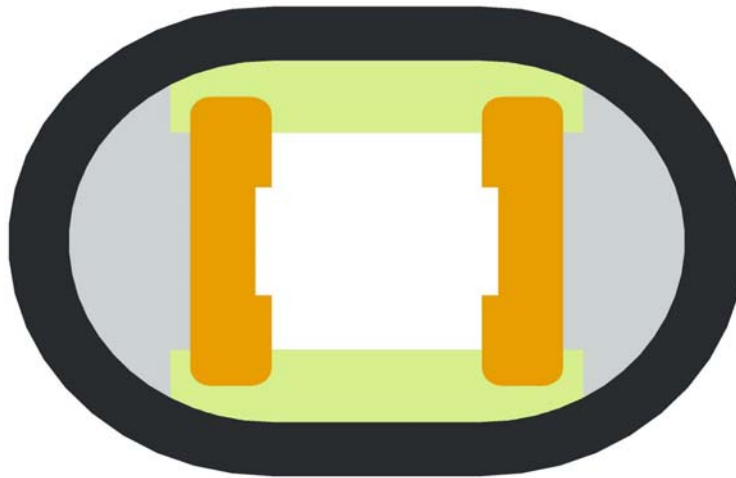
Scalloped Flat Rail Design
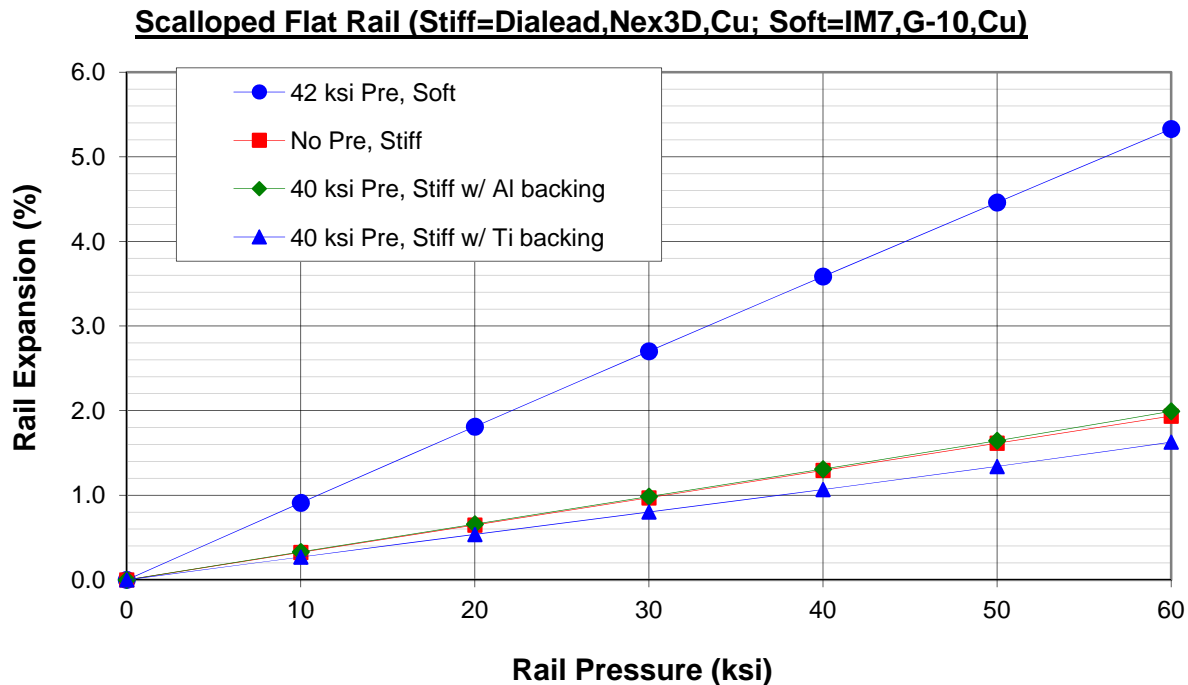

Figure 15. Scalloped Flat Rail Design

Figure 16. Scalloped Flat Rail Design Rail Expansion

The scalloped flat rail design was meant to incorporate the best parts of the other designs as well as HE rounds in a stiff structure. The sides of the cross section are flat to avoid any ovaling, and the rails have rounded corners to avoid hot spots and a cutout to hold the armature in place. The interlocking rails and insulators make assembly easier and help mitigate rail deflection should the preload ever be overcome. The backing behind the rail transfers the load to the wrap using a lighter material than copper. Overall, this design works better than most, but it is a bit heavier. Manufacturing the insulators might be a problem for this design.
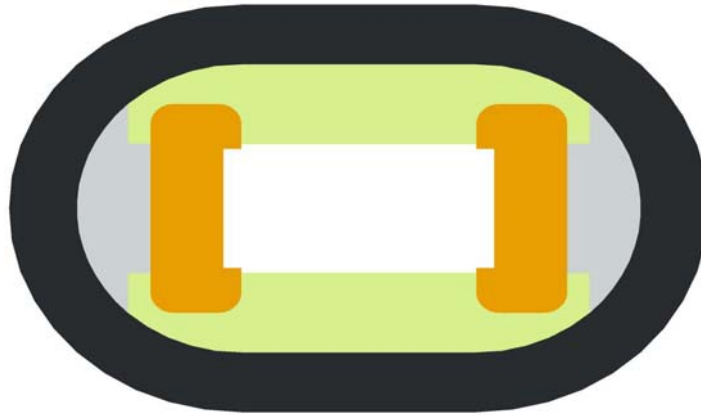
Flat Rail Design

Figure 17. Flat Rail Design

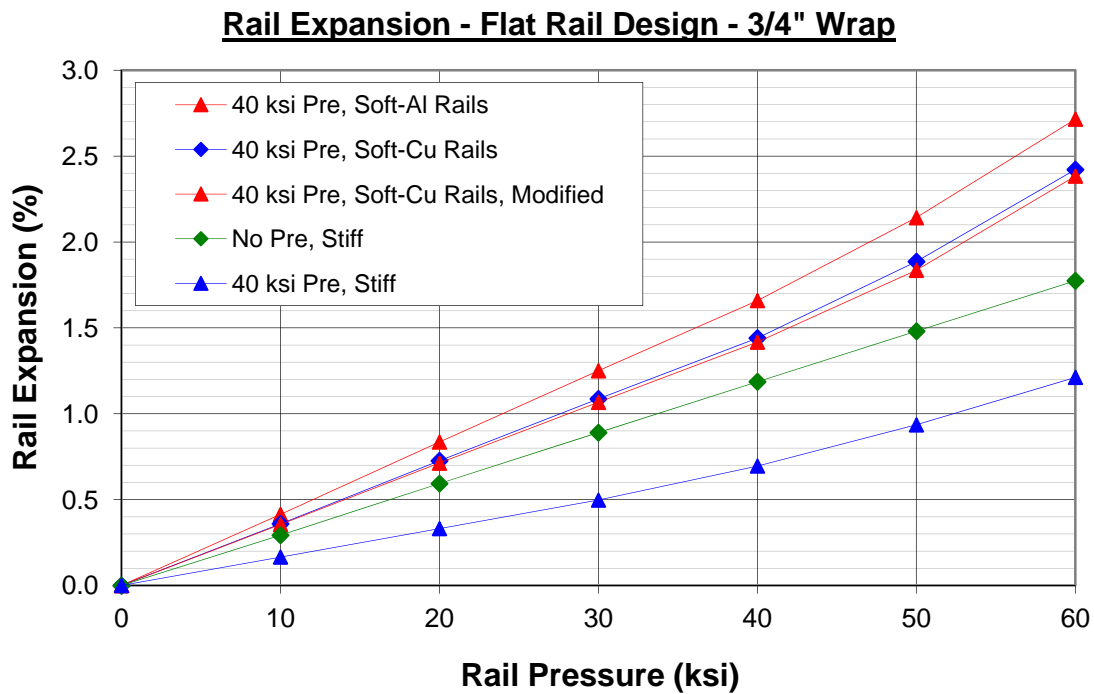**Rail Expansion - Flat Rail Design - 3/4" Wrap**

Figure 18. Flat Rail Design Rail Expansion

This design is the same as the scalloped flat rail design, except the scallop is not present. This makes the structure lighter and stiffer. The modified series on the plot represents a case where the insulator does not wrap all the way around the rail (see picture to the right). This shows that as long as preload is never overcome, the interlock is not needed to mitigate preload because the insulators are always in compression.
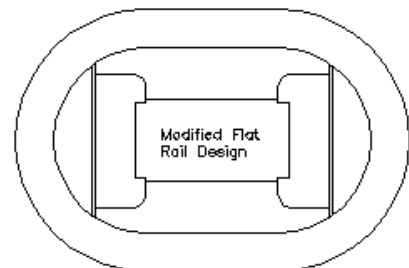
Design Comparison

The most basic design evaluations involve comparing the rail expansions for the different designs with the same wrap thickness and the same materials for all the parts. Two different groups of materials have been studied, the soft group and the large group. The soft group uses IM7 with a lay-up of 2 hoop layers to every axial layer for the wrap, G-10 for the insulators, and copper for the rails. The stiff group uses Dialead K63712 with a 2:1 lay-up for the wrap, Nextel 610 3D Weave for the insulators, and copper for the rails. For the flat rail designs, the backing piece is either aluminum or titanium for these studies. The goal for Milestone A was 0.5% rail expansion, while the threshold was 3% rail expansion. The other goal that needs to be considered is the ability to fire HE rounds. Firing KE rounds is the threshold.

The following plot compares the different designs using soft materials.

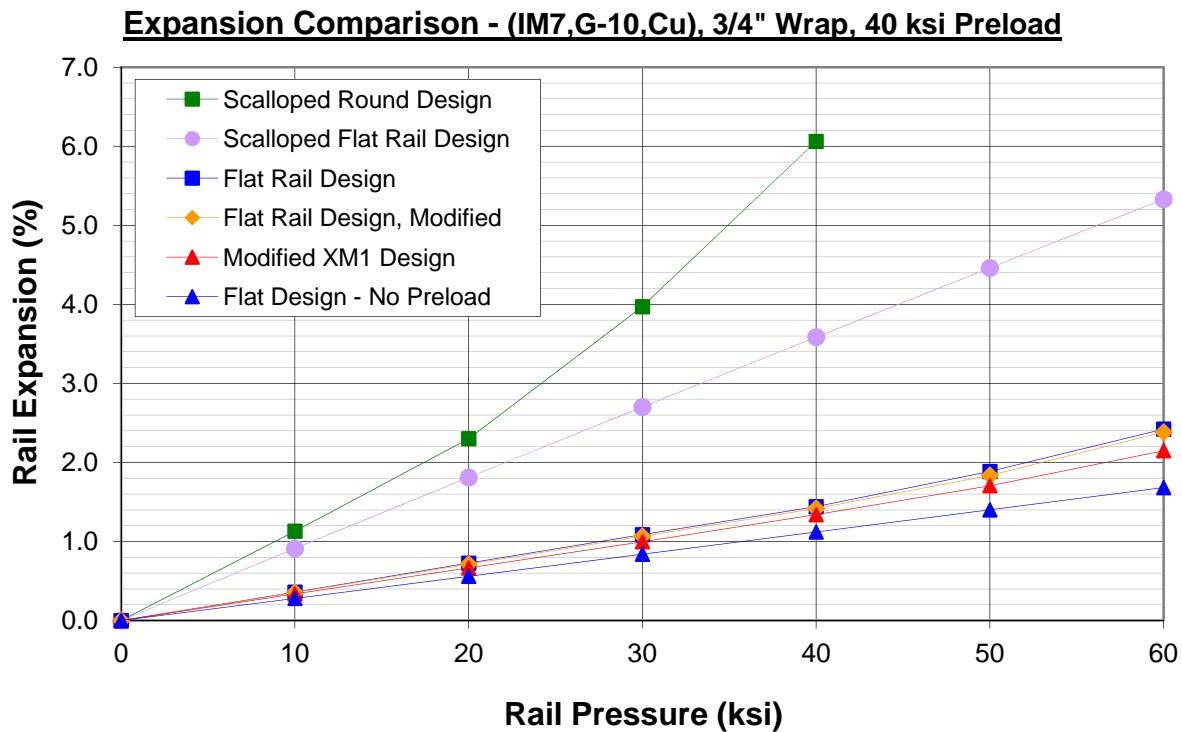**Expansion Comparison - (IM7,G-10,Cu), 3/4" Wrap, 40 ksi Preload**

Figure 19. Expansion Comparison with Soft Materials

The two scalloped designs do not perform well with soft materials, even with a large preload. The other designs, however, would easily achieve threshold for rail expansion at 30 ksi rail pressure, but would not achieve the goal. The flat design performs the best, getting approximately 0.84%, with the modified XM1 just behind it at 1%. The flat rail design is next at just under 1.1%. Any of these would work well for minimizing rail expansion with soft materials. The scalloped designs definitely need stiffer materials in order to function properly.

The next plot compares the different designs using stiff materials.

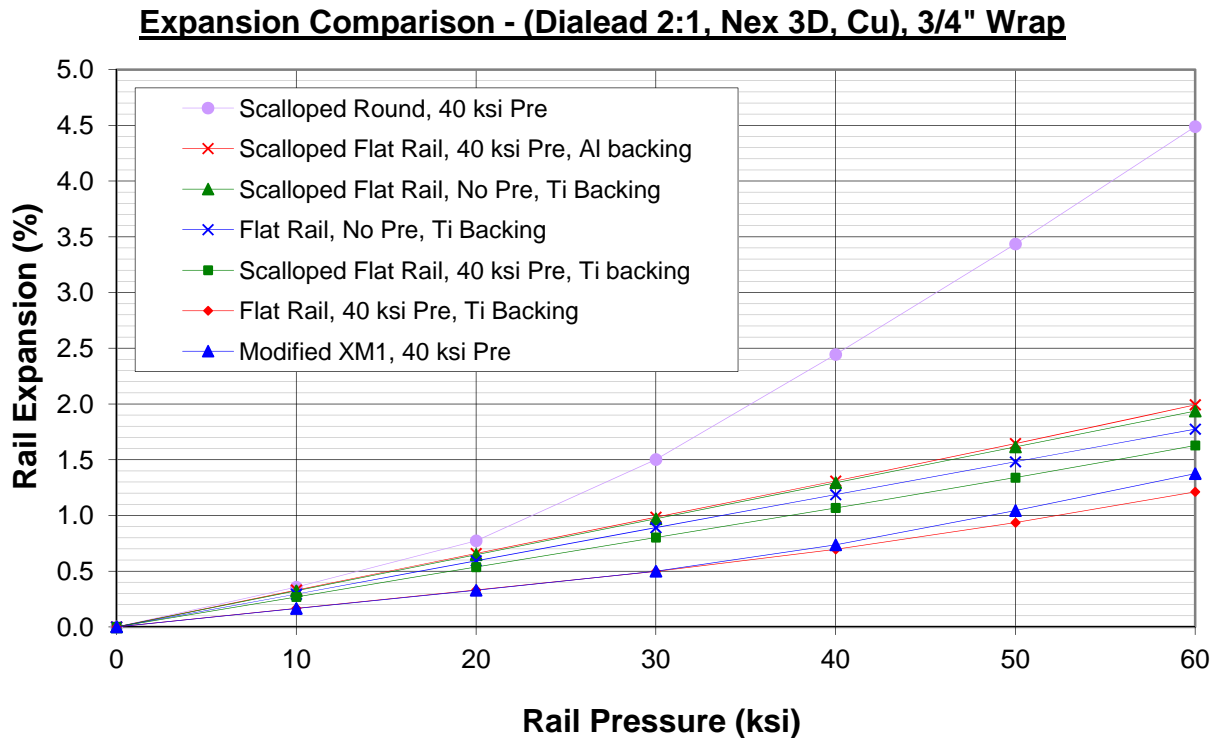## Expansion Comparison - (Dialead 2:1, Nex 3D, Cu), 3/4" Wrap

Figure 20. Expansion Comparison with Stiff Materials

The modified XM1 and flat rail designs are again the best (The flat design was not modeled with these materials), with both getting just under 0.5% rail expansion. This would meet the goal for rail expansion. The scalloped designs, with or without preload, and the flat rail design with no preload all are under 1%.

In order to meet the goal for rail expansion, either the modified XM1 design or the flat rail design could be chosen, but these do not meet the goal of firing an HE round. At this point, both goals cannot be achieved at the same time. To meet the goal of firing HE rounds, the scalloped flat rail design performs the best out of the two scalloped designs. A plot for several cases of this design is shown next.

Analysis of Scalloped Flat Rail Design

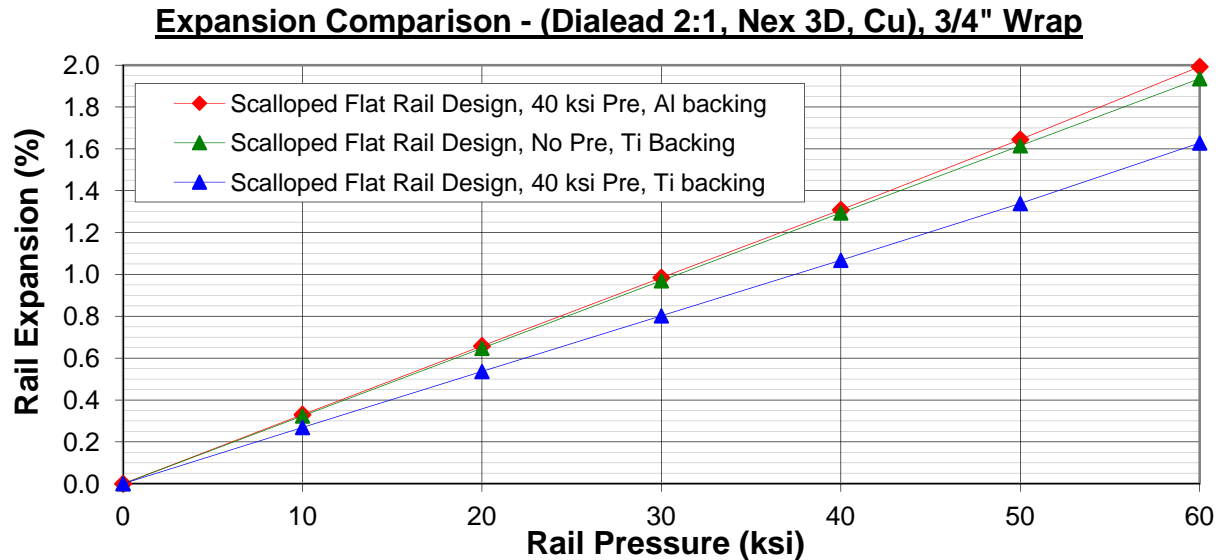## Expansion Comparison - (Dialead 2:1, Nex 3D, Cu), 3/4" Wrap

Figure 21. Rail Expansion for Scalloped Flat Rail Design with Stiff Materials

With a Titanium backing, 0.8% rail separation can be achieved. Even with no preload, the separation is still less than 1%. With an aluminum backing, the results are not as good, but they are still great for a scalloped design and would be much lighter than titanium.

In order to better understand the scalloped flat rail design, parametric studies were run with and without preload to see how rail expansion and weight would be affected by varying the thicknesses of the wrap and the insulator. The thickness of the insulator was varied from 0.8 inches to 2 inch, and the thickness of the wrap from 0.25 inches to 1 inch. The rail expansion was then plotted at 30 ksi vs. the weight of a 4 meter tube with those thicknesses. The following plots show the results.
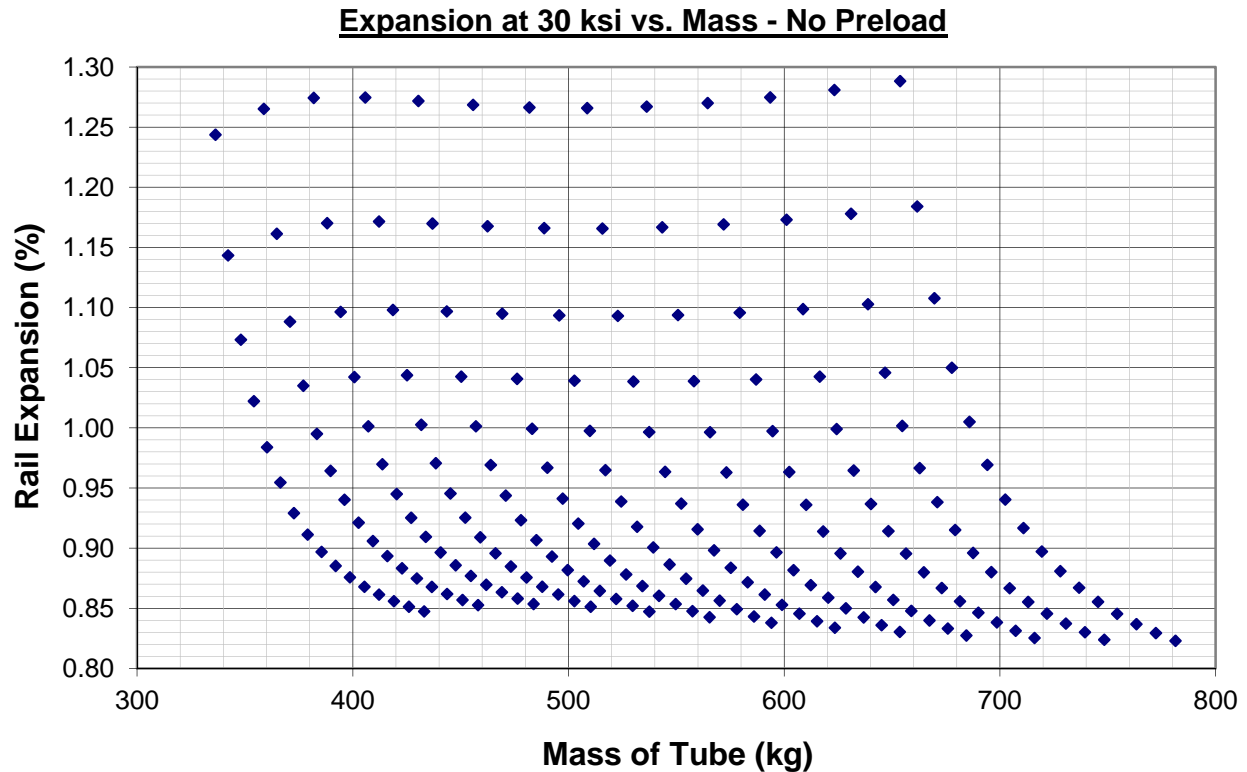
Expansion at 30 ksi vs. Mass - No Preload

Figure 22. Parametric Study Results for Scalloped Flat Rail Design with no preload

This plot gives an easy way to see what can be achieved with this design with no preload. It is difficult to show this on the plot, but the farther down on the plot, the larger the thickness of the wrap. The farther to the right on the plot, the thicker the insulator is. Using this information, it was determined that the thickness of the insulator does not affect rail separation nearly as much as the thickness of the wrap, which helps only marginally more the thicker it gets. With no preload, a thick wrap and a thin insulator give the best tradeoff between rail separation and mass of the tube.

For the preloaded case, the results are similar but different. With everything in the parametric study being the same with a 40 ksi preload added, the following plot was generated.
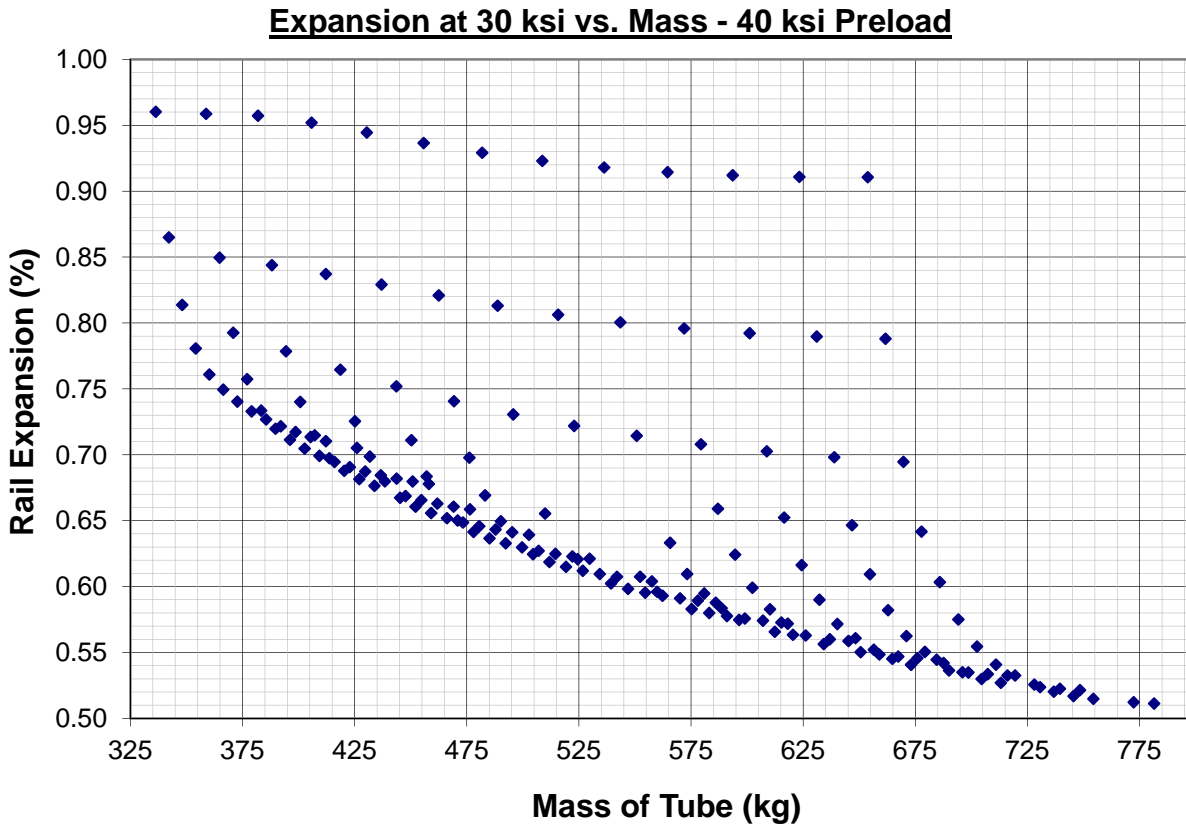
Figure 23. Parametric Study Results for Scalloped Flat Rail Design with 40 ksi preload

In the preloaded case, much lower rail separations can be achieved by adding extra weight. This has not been studied enough to determine the different affects of changing the insulator thickness vs. changing the wrap thickness, but this plot does show what can be achieved. What is known, however, is that the thickness of the insulator plays a much greater role in the preloaded case than in the case with no preload.

Pinch and Closedown

The next four pictures show how the designs deform during assembly and firing. For all four pictures, the shape of the design under 30 ksi loading and the shape of the design in the preload condition are superimposed over the original design. The scale factor for each drawing is 10, and each picture comes from the model which used stiff materials. The preload shape is blue, while the 30 ksi shape is red. Table 1 shows the values of the closedown between rails during preload, as well as the pinch caused by whichever part holds the armature in the center of the bore. Values are in thousandths of an inch, and pinch values are given during preload and during a rail loading of 30 ksi.

Table 1. Pinch and Closedown Comparison

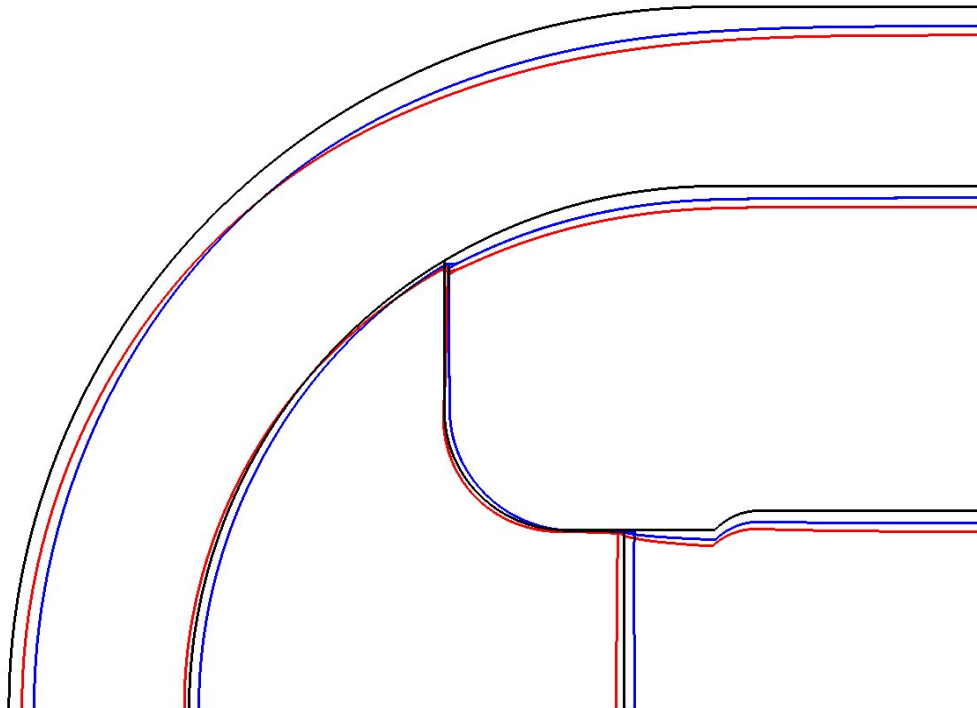| (thousandths)	Modified XM1		Flat Rail		Scalloped Flat Rail		Scalloped Round	
	Soft	Stiff	Soft	Stiff	Soft	Stiff	Soft	Stiff
Closedown	33.04	8.26	38.42	11.61	102.01	20.43	38.1	4.12
Pinch (Preload)	41.6	8.26	-1.9	-1.36	-22.98	-4.57	124.5	21.75
Pinch (30 ksi)	61.09	13.59	6.48	5.72	6.61	4.24	197.09	40.87

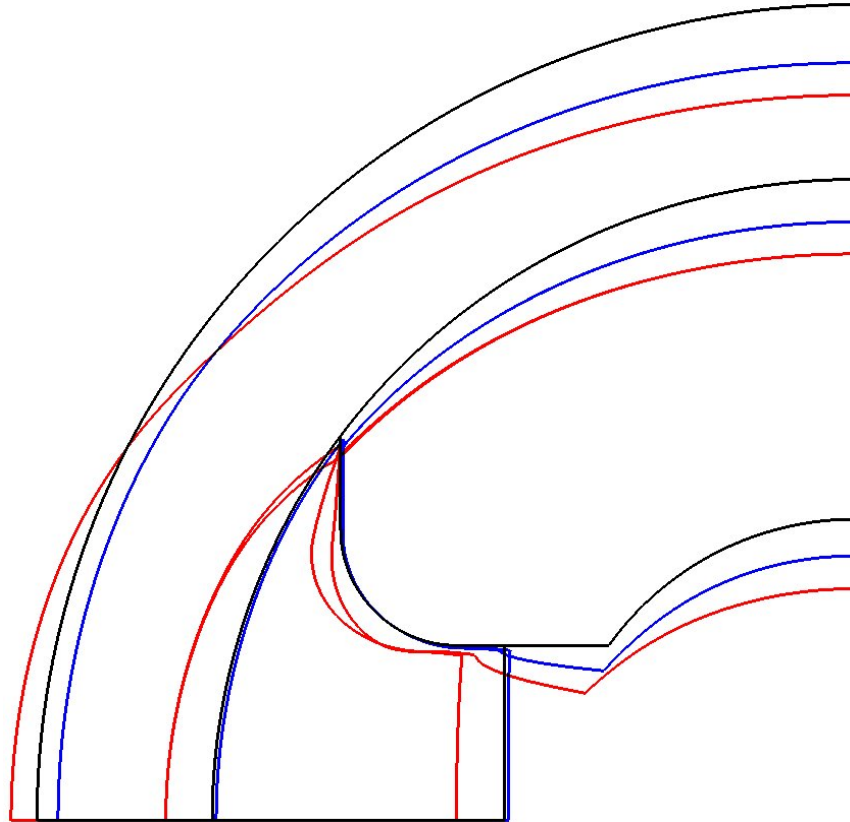Figure 24. Deformed Shapes for Modified XM1 Design

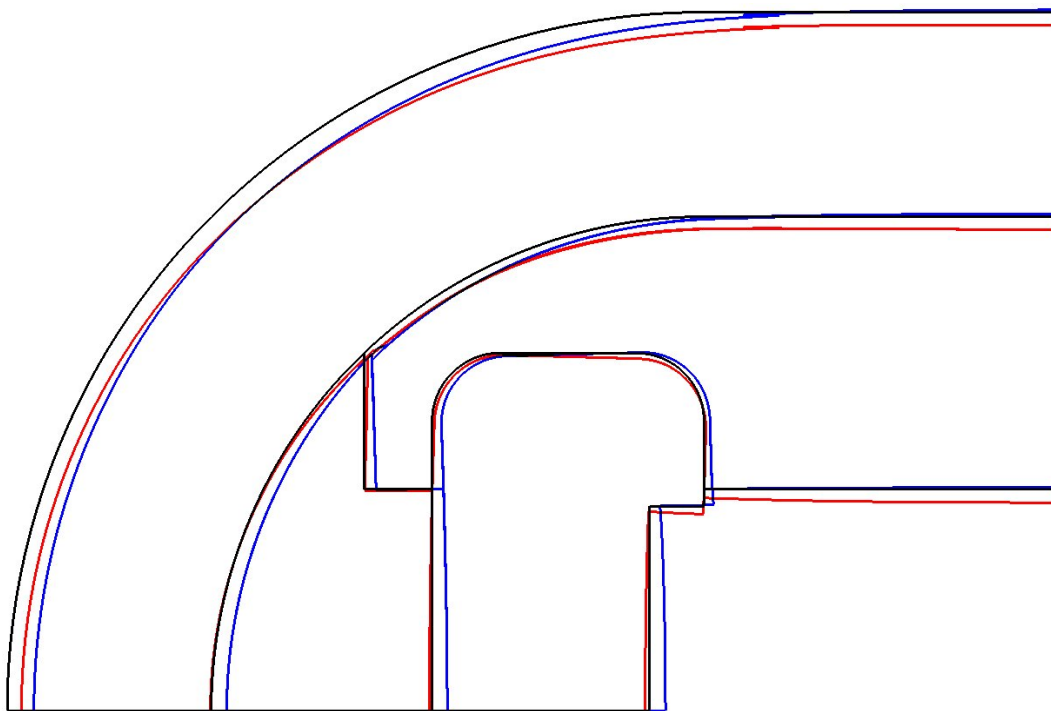Figure 25. Deformed Shapes for Scalloped Round Design

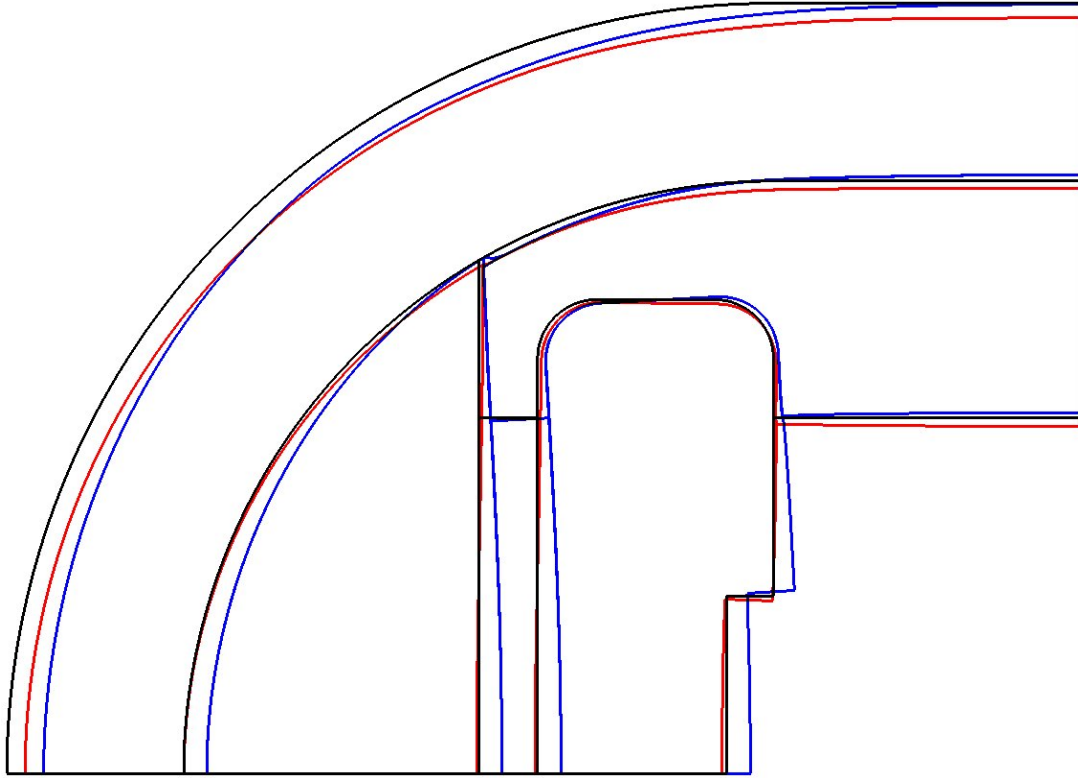Figure 26. Deformed Shapes for Flat Rail Design

Figure 27. Deformed Shapes for Scalloped Flat Rail Design

Parametric Study of Flat Design

When the flat design was first studied as an option, a parametric study was run that varied the thickness of the wrap and studied the effects of using different wrap materials. It was already known that the greater the stiffness of the material or the greater the thickness of the wrap, the lower the rail separation would be for a given load. But, it was not known how fast the benefits of thickening the wrap dropped off with increased thickness when using composite materials. The low out of plane modulus is the major cause of this problem. The load does not transfer well between layers of composite and the outside layers do not carry much load at all. When the thickness gets above approximately 1 inch, it is most likely not worth the weight penalty of adding extra material. Increasing the out of plane modulus would help this problem significantly, as the runs with steel as the wrap material shows. Isotropic properties help, but the weight gain is the problem there. The plot below shows the results of this parametric analysis and how this information about composite wrapping was learned.
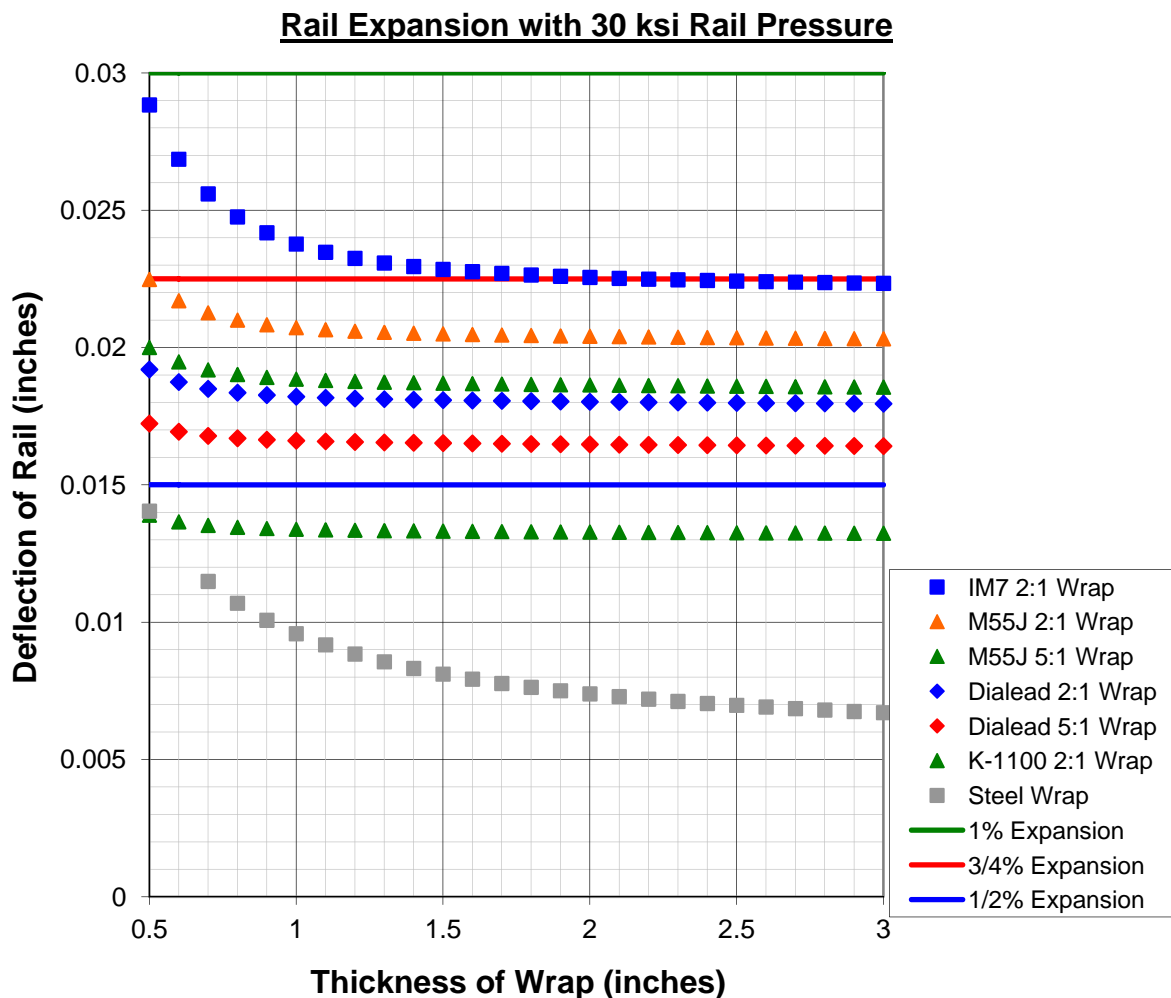

Figure 28. Parametric Study Results for the Flat Design

Overall Comparison

The weights and masses of the different designs, with both soft and stiff materials, are shown in the table below. These calculations used a wrap thickness of 3/4" and a length of 4 meters.

Table 2. Weights of the Designs with Soft and Stiff Materials

	Modified XM1		Flat Rail		Scalloped Flat Rail		Scalloped Round		Flat Design	
	Soft	Stiff	Soft	Stiff	Soft	Stiff	Soft	Stiff	Soft	Stiff
Weight (lb)	665.98	861.97	475.03	641.68	745.43	987.30	501.18	705.89	312.55	369.72
Mass(kg)	301.98	390.85	215.40	290.96	338.01	447.68	227.25	320.08	141.72	167.64

After going through this testing and modeling, it was decided that the materials that are most likely going to be used in the railgun are IM7 for the wrap, Nextel 610 for the insulator, and chromium copper for the rails. Table 3 gives a summary of the six design ideas by comparing various aspects of the designs. First, the rail expansion at 32 ksi is given as a comparison of the stiffness of the designs. This value for rail pressure is the predicted rail pressure during firing. The weights and masses of the designs are given in pounds per inch and kilograms per meter to make it easier to calculate the total weight or mass of the tube based on a certain length. The scalloped column addresses the issue of whether or not the design can fire HE rounds. Last but definitely not least, the risks column discusses the various problems with the designs, such as difficulties in manufacturing its parts or problems that might be encountered during firing.

Table 3. Comparison of EM Gun Cross Section Designs

Design	Picture	Rail Expansion (%) @ 32 ksi Rail Pressure	Weight (lb/in)	Mass (kg/m)	Scalloped ?	Risks
Flat Design		0.980	2.09	37.32	No	Would most likely fail with plasma fault
Flat Rail Design		0.604	3.59	64.05	No	Manufacturing difficulties: rail straightness and insulator
Scalloped Flat Rail		0.932	5.32	95.02	Yes	Manufacturing difficulties: rail straightness and insulator
Scalloped Round		1.759	4.16	74.25	Yes	Difficulty manufacturing insulator
Modified Flat Rail		0.686	3.59	64.05	No	Difficulty manufacturing insulator
Modified XM1		0.567	5.13	91.66	No	Design well understood

Conclusion

Based on the results from these studies, it was determined which cross sectional designs are good, and which ones are not so good. The Flat Design is very light and also fairly stiff without the need for a preload. If the problem of plasma pressure on the insulator sides of the bore can be overcome, and firing HE rounds is not a necessity, this would be a great design to use. The Flat Rail Design and the Modified Flat Rail Design are also both good designs, and would perform quite well if the insulators can be manufactured. The Scalloped Round Design would be easy to manufacture, but would not perform as well as the other designs in terms of rail pressure. The Modified XM1 Design is probably the best design at this time out of the different un-scalloped designs because it is well understood and proven from electromagnetic, structural, and manufacturing points of view. It also has the lowest rail expansion among these designs with these materials. The only problem is its weight because of the large copper rails. The Scalloped Flat Rail Design is at this point the best scalloped design. It has a very low rail deflection for a scalloped design and its weight is not much higher than the Modified XM1 Design. The problem with it is the same as the other flat rail designs - the insulators will be difficult to manufacture. Should HE rounds definitely be required in the future, this design should be analyzed further to determine if manufacturing it is feasible.

References

Littlefield, Dr. Andrew et al. *Carbon Fiber/Thermoplastic Overwrapped Gun Tube*. Gun Tubes Conference 2005, Oxford, England, 10-14 April 2005.

Wahrer, Don. "Launcher Barrel & Core." Launcher CDR Follow up, 30 April 2002.